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Compound-Core Active Multimode Fiber for High-Efficiency Fiber Laser System

Contract No: F49620-98-C-0085

Phase I Final Report

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1999

Altair Center proposed to develop a novel and innovative compound-core multimode active fiber for high-efficiency fiber laser systems capable to operate in a single-mode regime. The compound multimode core of the fiber is designed to support propagation of a higher order mode exhibiting a sharp peak of its field in the central region of the core. The sharp-peak mode extracts energy form the entire volume of the active fiber core and concentrates it in the core central region. The output sharp-peak beam is a well-collimated waveguide mode that can be easily focused and coupled into a standard single-mode fiber. The compound-core fiber has many unique properties including the ability to operate at several different wavelengths simultaneously, wavelength selective and filtering properties, high sensitivity of the central mode peak to the external perturbations of the fiber, etc. This suggests its numerous applications in active and passive fiber based devices and sensors.

During the Phase I project, the proposed concept was proved by simulating the fiber mode properties. Stable sharp-peak mode operation of the fiber is analytically demonstrated. The technological methods are developed to fabricate silica fibers with large value of Δn during the first two stages of the experimental part of the project. MCVD method with aerosol delivery technique permits to fabricate optical fibers with $\Delta n = 0.05\text{-}0.07$. This is the highest value of raised refractive index that has been obtained in a silica fiber. The central dip problem was not solved at the time because of an uncontrollable dopant ion diffusion. The last two stages of the project were directed to the new fiber preform fabrication method to overcome this problem. A rod-in-tube method was used to form the central dip area and Ta-doped silica tube was used to form the core ring area. Fiber with designed refractive index profile but with no concentric fiber core position was drawn. A total of seven fiber performs were fabricated. We believe that the results we obtained indicate a real possibility to produce an optical fiber with the desired design refractive index profile.

The proposed compound-core fiber is an excellent candidate as a product in several markets, including: fiber lasers, telecommunication, wireless optical communication, electronic printing, remote sensing and monitoring, industrial cutting and welding, parametric frequency conversion, sensors, medical applications, etc.

1. Introduction

Fiber lasers are widely recognized as an efficient means to generate light of a single transverse mode [1]. However, for a long time they have been generally regarded as low power devices for at least two reasons: the lack of high-power pump sources at suitable wavelengths and the difficulty of coupling the power from these sources into the fiber's single-mode core. Semiconductor laser diode technology offers an efficient and flexible source of optical power which has the potential to provide CW powers over 70 watts. Different power scaling methods have been proposed during the last few years resulting in demonstration of the fiber laser amplifiers having a power of over 35 watts at wavelength 1.1 μm [2-6].

The design of high power fiber lasers is a two-fold problem. The first part of the problem is the development of efficient rear-earth-doped active fibers for such lasers. The second part is the development of efficient means to pump such active fibers. The pump problem has been successfully solved by a number of companies demonstrated efficient means of laser-to-fiber pigtailing. Therefore, the main effort in the design of high-efficiency fiber laser systems should be concentrated today on the development of new types of active fibers.

Fabrication of active silica-based fibers using the sensitization of erbium (Er^{+3}) and ytterbium (Yb^{+3}) ions offers new pumping scheme with a wide range of possible pump sources and operating wavelengths. In contrast to Er^{+3}-doped fibers employing diode lasers pump at 980 or 1480 nm of Er^{+3} absorption bands, Er^{+3}:Yb^{+3} doped fiber can be pumped in a much broader range of spectrum. The pump power in this fiber is absorbed by Yb^{+3}, then it is transferred by ion-ion interactions to Er^{+3} ions. The broad absorption of Yb^{+3} over the 800 to 1100 nm band with peak at 980 nm extends the range of potential wavelength and provides a flexible and efficient means of pump which does not require precise wavelength stabilization [7]. This approach opens a door to the development of high power laser systems generating more than 10 W of CW power at eye safe wavelength of 1.5 μm.

Using double clad fibers having rectangular high aperture inner cladding and external low index polymer cladding have been demonstrated to be an efficient approach to power scaling of the fiber lasers and amplifiers [2,3,6]. This technology has already resulted in the commercially available products. Double-clad fibers and laser systems are available from Polaroid, Bell Laboratories, University of Southampton (UK), IRE-Polus, INO (Canada), etc. Specialty multi-clad fibers exhibiting one of the best performance were developed by a German-Russian company IRE-Polus which reported 9 W single-mode CW Erbium doped fiber laser at 1532-1610 nm.

In the double-clad fibers the multimode rectangular cladding having large cross section and high numerical aperture can more efficiently accept and propagate light from a laser diode having rectangular geometry of its active stripe or from a diode-laser array. The inner single-mode fiber core doped with an appropriate rare earth material gradually absorbs energy from the pump light as this light propagates down the multimode inner cladding. Although this method strongly improves coupling a pump light from the diode-laser array into an active single-mode fiber, it has considerable disadvantages.

In order to pump the active fiber core efficiently the light should propagate over a large distance in the passive fiber cladding. In such long fibers strong loss of the expensive pump power in the passive fiber cladding takes place and the fiber needs to be periodically re-charged. The double clad fibers can be employed in the systems not requiring extremely high pump intensities, such as neodymium doped fibers, when all required pump power can be delivered in a large cladding region in one stage. One stage pump scheme, however, can not be applied to erbium doped systems operating at eye-safe and one of the most important communication wavelength of 1.5 μm. They generally require higher pump intensities, and

efficient side couplers should be designed to couple more power in stages for "re-charging" the fiber along its length making the system very bulky and expensive.

With the rapid advances of fiber laser and amplifier technology, it is becoming more and more apparent that the physical limits of single-mode fiber technology are being approached. For example, a single-mode erbium fiber generating a maximum energy of 150 μJ was demonstrated [8]. This result was obtained with a single-mode fiber with a core diameter of 15 μm and a fiber N.A. of 0.07, which is roughly the maximum that is compatible with single-mode propagation at 1.55 μm. Any further increase in pulse energy requires an increase in core area, along with a lowering of the N.A. of the fiber for preservation of single-mode operation. This requirement in turn leads to an unacceptably high bend sensitivity.

The *multimode* active fibers having relatively large cross section can be efficiently pumped with laser diodes in one stage over their entire active volume. Therefore, length of such fibers can be made much shorter than the length of double-clad fibers simplifying the system design and reducing its cost. The multimode fibers, however, usually guide a large number of modes. Interference between these modes results in a complicated speckle pattern deteriorating the beam quality. Development of the multimode active fibers having large cross section and capable to operate in a single-mode regime would result in dramatic improvement of the fiber efficiency and decreasing the propagation distances required for signal amplification. Such fibers will considerably advance the entire optical fiber and fiber laser technology.

The advantage of increasing the fiber cross section have been already experimentally demonstrated in resent publication [8], where high-energy single fundamental mode ($M < 1.2$) operation of a Q-switched fiber laser based on a multimode large-mode area erbium doped fiber has been achieved. A passive large mode area photonic crystal fiber consisting of a pure silica fiber core with a regular array of small holes running through its entire length has been also recently demonstrated [9,10]. The refractive index difference between the pure silica core and "holey" cladding can support the single-mode operation even in the fiber having core diameter of about 100 μm.

However, such straightforward approach to the problem of increasing the mode area has very fundamental limitations. Increasing area of the fundamental mode in such fibers is achieved at the expense of undesirable decreasing the fiber numerical aperture resulting in difficulty of fiber pumping with diode lasers having large beam divergence and high bend sensitivity.

ALTAIR Center proposed more sophisticated solution of the problem using a compound-core multimode active fiber operating in a single-mode regime [11]. Such a multimode compound-core fiber having both large cross section and high numerical aperture can be efficiently pumped with laser diodes. Instead of using the fundamental fiber mode, the proposed approach takes advantage of a higher order mode in such a fiber having large mode area and efficiently extracting the energy from entire cross section of the active fiber. In order to make the fiber compatible with standard single-mode signal transmitting fibers, the compound fiber core should have a special refractive index profile providing generation of a higher order mode with a sharp central peak in which most of the mode power is concentrated. Such sharp-peak mode exhibits good focusing and collimating of the output beam which can be then efficiently coupled into a standard single-mode fiber. The compound-core fiber has many other unique properties including the ability to operate at many different wavelengths simultaneously, wavelength selective and filtering properties, regions of high sensitivity of the central mode peak to the external perturbations of the fiber, etc. This suggests its numerous applications in active and passive fiber based devices and sensors.

The proposed compound-core fiber for high-power fiber laser is an innovative device, with performance features well beyond state-of-the-art technology. One of the most important properties of this fiber is its capability to operate at several different wavelengths providing almost perfect overlap between sharp peaks of the modes at different frequencies. Therefore, the fiber system, which is originally designed to operate in the infrared range of spectrum, can be conveniently characterized and aligned at visible wavelength using simple HeNe laser. Although the sharp-peak mode has broad regions of stability, under certain conditions in can be made extremely sensitive to the variation of the fiber parameters. This property can be used in all-fiber-in-line Q-switch and mode locking components for generation of short laser pulses and also in various fiber sensors. Spectral selectivity of the compound-core fiber can be used in all-fiber-in line wavelength filters. The compound-core fiber system offers many advantages over the conventional double clad fibers, which can be summarizes as follows:

- Much shorter fiber length,
- Higher optical damage threshold
- Higher pump efficiency, one stage pump scheme
- Operation at several wavelengths simultaneously
- Spectral selectivity, filtering
- High mode sensitivity for all-fiber-in line Q-switching and mode locking
- Sensor applications

Phase I of the program was addressed to theoretical simulation of the compound-core fibers with idealized model refractive index profile, developing new technology for their fabrication, fabrication of the passive compound-core fiber, demonstration of the mode with sharp central peak and characterization of the fiber properties. During the Phase I project we performed mathematical modeling, characterized and studied mode properties of the compound-core fiber theoretically, developed new technology for manufacturing such a fiber, fabricated several preforms with required high index contrast, performed drawing the fiber and characterization of its index profile. Since Phase II proposal was not selected for funding the work on fabrication of an active version of the compound-core fiber and its characterization cannot be continued in frame of this project.

During the Phase I project we have already began developing a strategy for successful commercialization and aggressive marketing of the compound-core fiber laser system. Two potential partners have been identified and technical contacts have been established. A laser manufacturing company, Semiconductor Laser International, Inc. has already expressed its interest in commercializing the high power fiber laser systems based on the innovative compound core fiber. The private investments in the project are almost guaranteed, based on the interest our innovative concept has received in discussions with the commercial partners.

2 Proof of Concept - Phase I Accomplishments

During the work on Phase I project we performed mathematical modeling, characterized and studied mode properties of the compound-core fiber theoretically, developed technology for manufacturing such a fiber, fabricated several preforms with high index contrast and required index profile, performed drawing of the compound-core fiber and characterization of its profile. Moreover, ALTAIR has already started initial work on commercialization of the compound-core fiber and achieved preliminary agreement with two laser manufacturing companies about joint fabrication of the product.

Our systematic theoretical study of mode properties of the compound-core fiber and developed technology for its fabrication prove the proposed principle as a working concept. Results of the Phase I feasibility study are summarized in Table I.

Table I. Assessment of accomplishments against original Phase I objectives.

TASK	OBJECTIVE	MAIN RESULTS	CONCLUSIONS, ACCOMPLISHMENTS
Theoretical simulation	Model and characterize mode properties of compound-core fiber	Mode structure of a compound-core fiber with idealized model index profile is simulated. A sharp-peak mode is demonstrated and its stability is investigated.	Sharp-peak mode is a periodic function of wavelength and has broad regions of stability. Asymmetry in the fiber profile is not critical for the fiber performance. Optimum compound-core profile is identified for experimental fabrication.
Fiber design and fabrication	Develop technology for fiber fabrication. Fabricate preform and draw the fiber	Technology for fabricating preforms for compound-core fiber was identified. Several preforms with index contrast as large as 0.03-0.07 are fabricated.	Tantalum doping in the core has proved to be more successful then germanium with regard to the reduction of stress. Rod-in-tube method is used for fiber fabrication.
Experimental study of the fiber	Demonstrate the mode with sharp central peak. Characterize the fiber performance.	Fiber refractive index profile is characterized.	Fiber core still exhibits some asymmetry. Increasing the number of layers can solve the problem.
Data analysis and modeling	Analyze the obtained results, formulate recommendations	Analysis of the results of theoretical simulating compound-core fiber is performed.	Mode properties of the compound-core fiber are analyzed. Stable sharp-peak mode is demonstrated. Fiber profile providing operation at two wavelengths of 632.8 nm and 1.55 μm is identified.
Design Phase II apparatus	Identify design parameters and components for Phase II prototype fiber laser system. Identify commercial partners.	Two potential partners are identified for commercialization of the developed system.	Conceptual design of the prototype apparatus and its components are identified.
Reporting results	Summarize results in reports and formulate recommendations for Phase II.	Challenges and accomplishments detailed in Status Reports and Final Report.	Three Status Reports, Progress Report and Final Report are prepared.

The following are main accomplishments in the Phase I project by the date of filing this Phase II proposal:

- ***Wavelength stability of the sharp-peak mode is theoretically demonstrated***

The sharp peak mode appears periodically as a function of wavelength and generally has the region of stability of about 20-30 nm, depending on the waveguide parameters. For example, the same compound-core fiber can exhibits the sharp-peak mode at wavelength 632 nm, 810 nm, 1.1μm, 1.2μm, 1.5μm, 1.6μm, 1.8μm, etc. In fiber laser applications, the sharp-peak mode can be achieved simultaneously at the wavelength of generation and at the pump wavelength.

- ***Stability of the sharp-peak mode to fiber profile asymmetry is theoretically demonstrated***

By artificially changing symmetry of the fiber core we demonstrated that the sharp peak mode is the most stable mode. This suggests a method of mode discrimination and suppressing generation of undesired higher order modes without sharp peak by fabricating slightly asymmetric compound-core fiber. The region of mode stability depends on the fiber parameters. It was demonstrated that operation of the fiber at longer wavelength is more forgiving to the core asymmetry then at shorter wavelength. In order to make the sharp-peak fiber more stable, one should decrease the fiber core diameter.

- ***An optimum compound-core fiber profile is identified for experimental fabrication***

Based on the obtained results, we designed an optimum compound-core fiber to be compatible with a standard single-more Corning fiber SMF-28 having core diameter 8.3 μm, numerical aperture NA=0.13, and mode diameter of 10.5 μm @ 1.55 μm. The goal was achieving good overlap between the fundamental mode of this single-mode fiber and the sharp central peak of the compound-core fiber mode. Moreover, the fiber was also designed to provide operation at wavelength 1550 nm and 632.8 nm simultaneously. This allows us to use a diode laser and HeNe laser for experimental characterization of the fiber properties.

- ***Technology for fabrication of passive compound-core fiber is developed.***

The technological methods have been developed to fabricate silica fibers with large value of Δn_2 during the first two stages of the project. MCVD method with aerosol delivery technique permits to fabricate optical fibers with Δn_2 =0.05-0.07. We believe this is the highest value of raised refractive index that has been obtained in a silica fiber. The central dip problem was not solved at the time because of an uncontrollable dopant ion diffusion. The last two stages of the project were directed to the new fiber preform fabrication method to overcome this problem. A rod-in-tube method was used to form the central dip area and Ta-doped silica tube was used to form the core ring area. Fiber with designed refractive index profile but with no concentric fiber core position was drawn. A total of seven fiber perform were fabricated. We believe that the results we obtained indicate a real possibility to produce an optical fiber with the desired design refractive index profile.

- ***Potential partners for commercialization of the compound-core fiber laser system are identified***

Preliminary agreements with two laser manufacturing companies are achieved about joint fabricating and commercialization of the fiber laser system based on innovative active compound-core fiber.

3 Technical Details and Phase I Results

3.1 Compound-core Fiber

The basic properties of the proposed compound-core fiber can be explained with the illustration of a planar compound waveguide structure. Generalization to the case of a circularly symmetric compound-core fiber is straightforward. The compound waveguide comprises a multimode core with refractive index n_2 and low index cladding having refractive index n_{cl}. Refractive index profile of the compound waveguide exhibits a large dip in its central region where the refractive index n_1 is slightly higher than that of the cladding but much lower than the core. By controlling the parameters of the compound waveguide, the energy of the highest order mode can be mostly localized in central low-index region of the core where the mode field exhibits a sharp peak. Figure 1 shows the refractive index profile of a planar compound waveguide structure and a simulation of its highest order guided mode exhibiting a sharp central peak.

Figure 1(b) is a simulation of the highest order mode for the case when the wavelength (λ) is 1.55 μm, and the respective refractive indices (n) and dimensions (d) for the different regions are as follows: n_{cl} = 1.460, n_1 =1.463 n_2 = 1.65, d_1 = 8 μm and d_2 = 30 μm. Since the fields of all other modes are localized outside the central region of the waveguide, they do not contribute if the central mode peak is selected by some aperture in the central region of the waveguide. The width of the mode peak can be controlled to match the aperture of a single-mode fiber by adjusting the refractive index n_1 and thickness d_1. This waveguide mode can be selectively excited by a Gaussian beam matched to the sharp central peak.

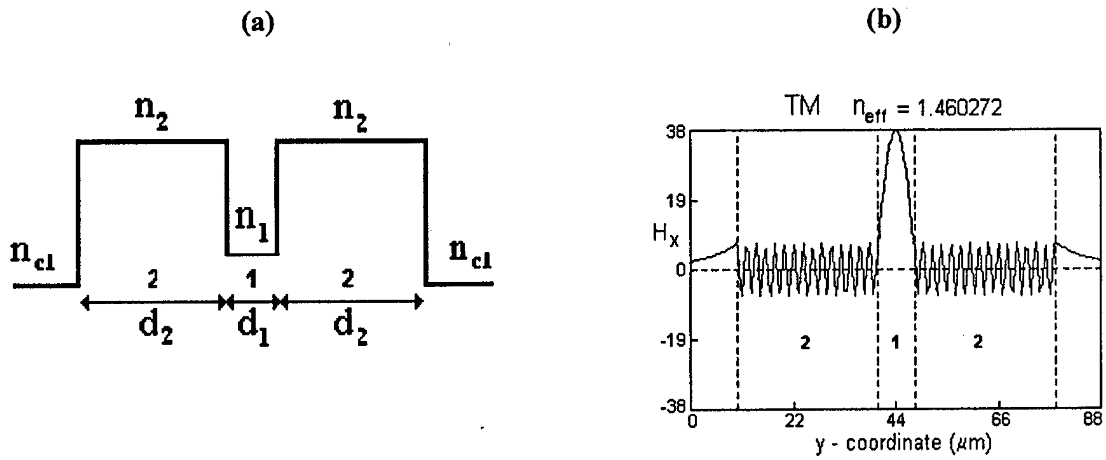

Figure 1: A planar compound waveguide structure: (a) its refractive index profile and (b) the highest order guided mode with a sharp central peak.

Since most of the mode power is localized in its sharp central peak, such a mode will efficiently extract the power from entire volume of the active fiber and concentrate it in the central region of the core. Following the theory of waveguides, mode peaks appear periodically as a function of its refractive index, dimensions and incident wavelength.

The normalized amplitude of the mode field in the waveguide is shown in Figure 2 as a function of wavelength and also as a function of the index of refraction. The periodic dependence of the mode peak intensity as a function of wavelength shows that compound-core fiber is capable to operate at many different wavelength simultaneously.

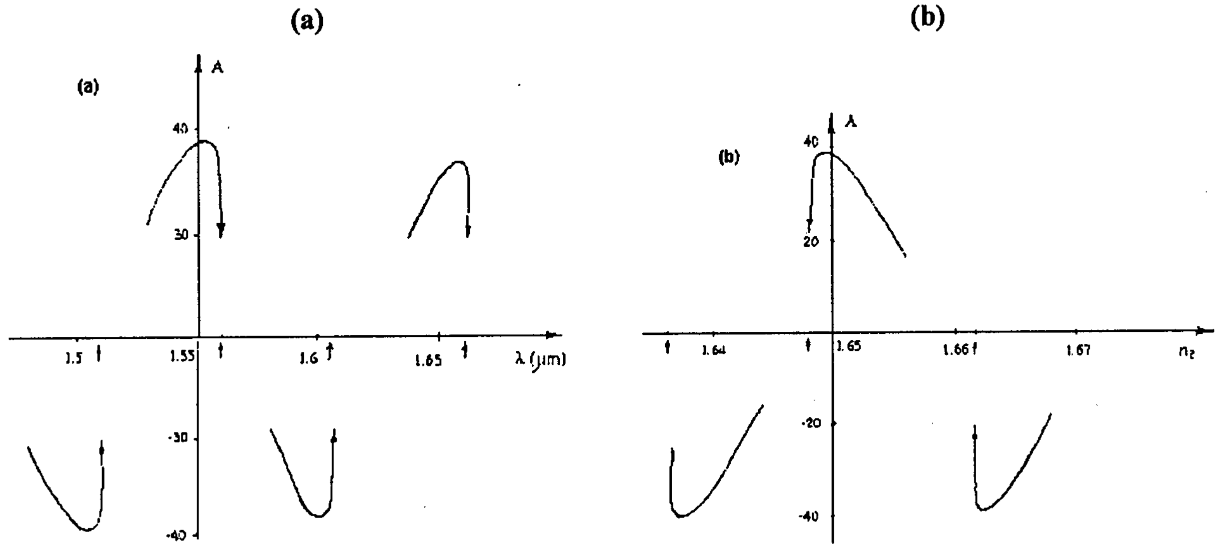

Figure 2: Periodic dependence of the mode peak amplitude as a function of: (a) incident wavelength and (b) refractive index of the waveguide.

It is possible to find a combination of waveguide parameters where the sharp-peak modes in the infrared and visible ranges of spectrum have similar strongly overlapping mode field configurations and very close effective refractive indices (phase matching). This remains valid for all spectral components within bandwidths of the mode peak stability corresponding to both modes. This unique property can be used for convenient characterization of the fiber designed to operate in the infrared range of spectrum using a beam from a simple HeNe laser at wavelength of 0.63 μm.

The amplitude of the central peak of the mode field has the similar periodic dependence on both the waveguide core refractive index n_2 and the waveguide thickness d_2. In the case of a planar compound waveguide under consideration, this property takes place for both states of polarization, the TE and TM modes. Amplitude of the peak of the transmitted beam sharply decreases near the cut-off of the waveguide modes when the index is varied by as little as 10^{-4} to 10^{-5}. Due to its high sensitivity and tunability, such a structure can be used as an all-fiber-in-line Q-switch and mode locking device for the generation of short laser pulses. Similarly, due to its strong wavelength dependence, the structure can also be used as a narrow band optical filter which shows a drastic decrease in transmission by varying the wavelength by only 0.1 nm. High sensitivity of the sharp peak mode in compound-core fiber near the cut-off and its spectral selectivity can also be used in various optical fiber sensors.

Perhaps one of the most interesting application the unique property of the compound waveguide structure to provide perfect phase matching and mode field overlap between sharp peak modes at different wavelength can find for frequency conversion and doubling in nonlinear waveguides and for phase matching of different spectral components in the design of optical parametric oscillators. The perfect phase matching in this system provides very large coherent lengths. Since the phase matching in the system is assisted by the waveguide structure and is not dependent on the birefrengent properties of material, a much broader selection of nonlinear materials can be employed in this system.

Let us suppose that the nonlinear compound waveguide structure is pumped with a powerful beam at frequency ω_p. As a result of three-wave mixing processes in nonlinear region where waveguide mode has its peak, two other modes at signal ω_s and idler ω_i frequencies are generated, where $\omega_p = \omega_s + \omega_i$, and

the modes satisfy the corresponding phase match condition. In the case of parametric oscillator, end faces of the compound waveguide have mirrors which are transparent at frequency ω_p and highly reflecting at other frequencies. The pump beam at frequency ω_p passes through the resonator, while signal and idler beam at frequencies ω_s and ω_i respectively are trapped in the resonator. In the case when the mirrors are made to be transparent also for the beam at idler frequency, the system operates as a singly resonant optical parametric oscillator generating output beam at signal frequency ω_s. Tuning the system to an operation point, where it has almost the same field configurations with sharp central peaks inside nonlinear central region for the beams at all three frequencies, provides good overlap between these fields as required for efficient frequency conversion.

Note that mirrors on the waveguide end faces are not necessary in counterpropagating configuration of optical parametric oscillators and amplifiers. The feedback appears in this case as a result of interaction between counterpropagating signal and idler waves. It is very difficult to realize such a parametric oscillator based on standard scheme, since it is almost impossible to find nonlinear materials with high birefringence required for achieving phase matching. The optical parametric oscillator based on a compound waveguide structure provides a unique possibility for realization of the phase matching. Such optical parametric oscillator may find many potential applications as amplifiers and sources of tunable optical radiation.

The optical parametric oscillator described above can be combined with a laser pumping this oscillator. In this case multimode region of compound waveguide should comprise an active material which being pumped with some external beam generates light at pump frequency ω_p. To provide a feedback for the light at pump frequency ω_p , mirrors should be made completely reflecting at this frequency.

As an example to demonstrate the feasibility of Altair's approach, consider a compound multimode waveguide for frequency doubling made from a Nd:YAG and a nonlinear KTP crystal. A combination of these two materials fabricated as a compound waveguide structure provides the efficient generation and frequency doubling of 1064 nm to 532 nm within the same compound waveguide structure. The cladding regions of the compound waveguide are made from KTP crystal, while the central low index region is made from doped KTP crystal to yield a slight increase its refractive index. The waveguide region is made from a Nd:YAG crystal. The dimensions of this systems are modeled with d_1 = 8 μm and d_2 = 20 μm. Figure 3 shows the orientation of the KTP where the incident radiation propagates along Y axis, which implies that the wave vector k is in Y direction and $\theta = \pi/2$.

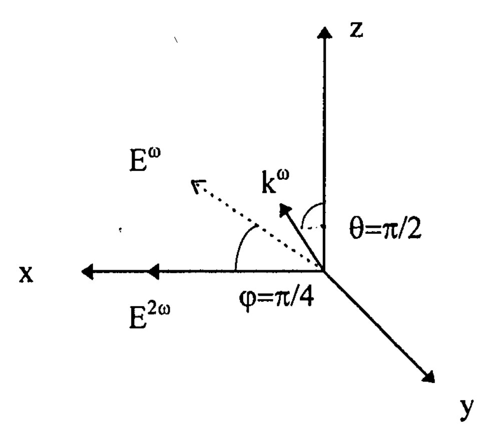

Figure 3: **Orientation of the KTP crystal axis with the incident radiation propagating along the Y axis.**

If the fundamental frequency beam (E^{ω}) is polarized at an angle $\varphi = \pi/4$ to X axis, then the doubled frequency beam ($E^{2\omega}$) is polarized in X direction having power

$$P^{2\omega} = 2\, d_{15}\, E_x^{\omega}\, E_z^{\omega}$$

where the large nonlinear coefficient for KTP crystal, $d_{15} = 6.1$pm/V, was used. The KTP crystal as the central layer of the waveguide is doped to increase its refractive index by 0.002. For such a configuration of the system, the compound waveguide structure exhibits the following refractive indices for the fundamental frequency (1064 nm) and for doubled frequency (532 nm) correspondingly:

$$n_{cl}^{\omega} = 1.7794,\ n_1^{\omega} = 1.7814,\ n_2^{\omega} = 1.817,\ n_{cl}^{2\omega} = 1.7787,\ n_1^{2\omega} = 1.7807,\ n_2^{2\omega} = 1.840.$$

A simulation of the mode field configuration exhibiting sharp central peaks for both the fundamental and doubled frequency modes are shown in Figures 4(a) and (b) respectively. The fundamental frequency mode and doubled frequency mode have almost perfect overlap of their mode field in the region of central peaks. Effective refractive indices of these modes are almost identical and hence the coherence length (L) in this case is equal to

$$L = \lambda/2(n_{eff}^{2\omega} - n_{eff}^{\omega}) \approx 3.2 \text{ mm}.$$

This large coherence length can be increased to a few centimeters after optimization of the system. The same compound waveguide structure can be used for generating higher order harmonics and for efficient parametric frequency conversion in optical parametric oscillators, if parameters of the waveguide are tuned to support phase matching and good mode overlap between the fundamental and converted frequency beam.

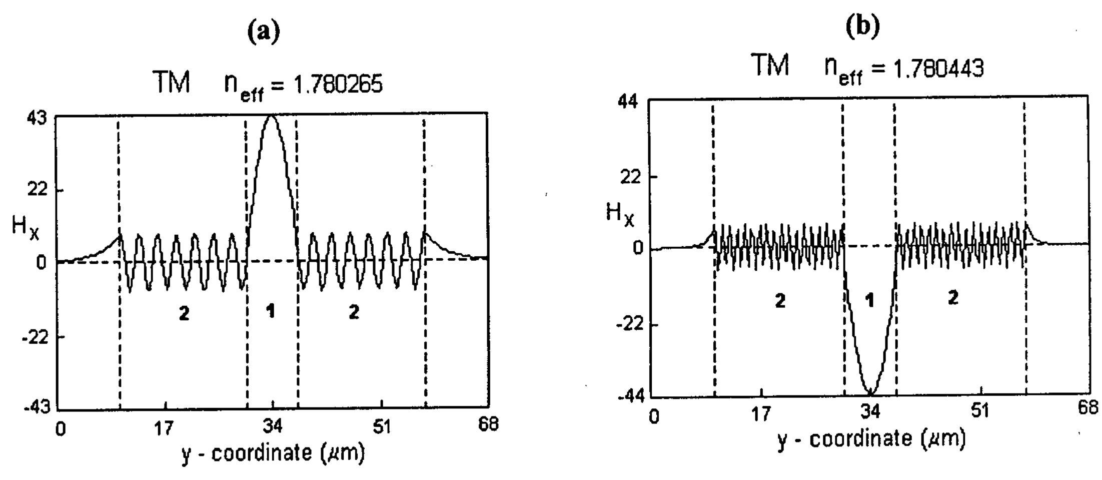

Figure 4: **A simulation of the mode field configuration exhibiting sharp central peaks for: (a) the fundamental and (b) the doubled frequency mode**

Our simulations unequivocally demonstrated a possibility of phase matching for a spectral range of 50 nm within the region of mode peak stability for the above configuration. The difference in effective refractive indices between the fundamental and second harmonic for different spectral components is so small that theoretically coherent lengths for them can be up to 5 cm. This implies that the beam can be

efficiently frequency doubled after propagating through a few millimeters of nonlinear compound waveguide structure.

The large cross section of the multimode compound waveguide made from Nd:YAG crystal can be pumped with a laser diode source to generate the fundamental wavelength at 1064 nm. Providing a feedback in the central region of the waveguide automatically selects the highest order mode with sharp central peak. Almost 87% of the energy of the mode peal is concentrated in the nonlinear central region of the waveguide made of KTP crystal. This creates a condition for the simultaneous generation and efficient frequency conversion or doubling within the same waveguide. The unique ability of the compound waveguide structure to support phase matching over a large coherent length provides efficient generation of visible radiation at 532 nm.

3.2 Theoretical Simulation and Design of the Compound-core Fiber

The main task for the fist few months of the project was theoretical analysis and design of the compound core fiber, study its basic properties. Using the methods of modern waveguide theory we have performed simulation of the compound-core fiber and investigated its mode characteristics. The analysis was based on the Helmholtz scalar wave equation. Since the fiber possess a circular symmetry, it was possible to reduce the problem to analysis of a one-dimensional case. Figure 5(a) schematically shows idealized model refractive index profile of the compound-core fiber. A sharp-peak mode in the fiber is shown in Figure 5(b).

We performed numerous simulations of the compound core fibers with different parameters in order to investigate their property, optimize the fibers for efficient application in the fiber lasers and to identify parameters of the compound-core fiber, which should be fabricated for experimental demonstration.

The first set of simulations was performed for the fiber having quartz cladding $n_{cl} = 1.457$ @ 632.8 nm, diameter of depressed central core region $d_1 = 8$ μm, core diameter $d_1 + 2d_2 = 62.5$ μm. The following model index contrasts have been used: $\Delta n_1 = n_1 - n_{cl} = 0.003$, $\Delta n_2 = n_2 - n_{cl} = 0.03$. Such a fiber has the numerical aperture NA = 0.3.

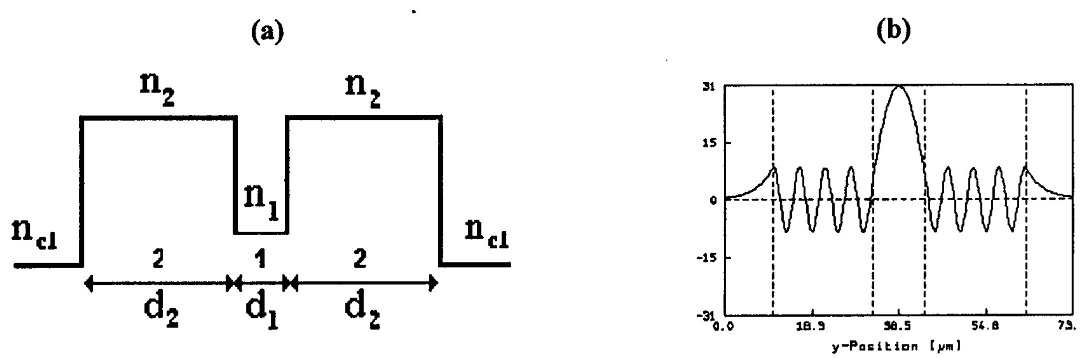

Figure 5: Compound-core index profile (a) and the sharp-peak highest order mode (b).

Among the most important issues addressed to in these simulations were the following:

- Wavelength stability of the sharp-peak mode

The sharp peak mode appears periodically as a function of wavelength and generally has the region of stability of about 20-30 nm, depending on the waveguide parameters. For example, the same compound-

core fiber can exhibits the sharp-peak mode at wavelength 632 nm, 810 nm, 1.1μm, 1.2μm, 1.5μm,1.6μm, 1.8μm, etc. In fiber laser applications, the sharp-peak mode can be achieved simultaneously at the wavelength of generation and at the pump wavelength.

- Stability of the sharp-peak mode to fiber profile asymmetry.

By artificially changing symmetry of the fiber core we demonstrated that the sharp peak mode is the most stable mode. This actually suggests a method of mode discrimination and suppressing generation of undesired higher order modes without sharp peak by fabricating slightly asymmetric compound-core fiber. It was demonstrated that operation of the fiber at longer wavelength is more forgiving to the core asymmetry then at shorter wavelength. For example, in the case of operation at wavelength $\lambda = 632$ nm, the sharp-peak mode remained stable up to the profile asymmetry $\Delta d \approx \lambda/10$, while for the same fiber at wavelength $\lambda = 1.5$ μm the asymmetry up to $(3/4)\lambda$ did not result in the mode instability. The region of mode stability depends on the fiber parameters. In order to make fiber more stable, one should decrease its core diameter d_2. For example, for the fiber with $d_2 = 15$ μm, the region of mode stability even at wavelength of 632 nm approaches 500 nm which is about 0.8 λ.

- Design of an optimum compound-core fiber for experimental fabrication.

Based on the obtained results, we designed an optimum compound-core fiber to be compatible with a standard single-more Corning fiber SMF-28 having core diameter 8.3 μm, numerical aperture NA=0.13, and mode diameter 10.5 μm @ 1.55 μm. The goal was achieving good overlap between the fundamental mode of this single-mode fiber and the sharp central peak of the compound-core fiber mode. Moreover, the fiber was also designed to provide operation at wavelength 1550 nm and 632.8 nm simultaneously. This allows us to use a diode laser and HeNe laser for experimental characterization of the fiber properties. The optimized compound-core fiber proposed for fabrication will have the following parameters: $d_1 = 11$μm, $d_2 = 21$ μm, $\Delta n_1 = n_1 - n_{cl} = 0.003$, and $\Delta n_2 = n_2 - n_{cl} = 0.03$. The sharp-peak mode in this fiber at wavelength 1.55 μm is shown in Figure 5(b). The fiber will have a standard 125 μm silica cladding and core with depressed central region.

3.3 Fabrication of Compound-Core Fiber

In our experimental effort, we have attempted to realize the proposed compound-core multimode fiber supporting propagation of a sharp-peak mode which intensity distribution mimics single-mode behavior. The idealized refractive index profile of this fiber is shown in Figure 1. Several problems were encountered in the fabrication of this fiber. First, there was a large refractive index difference between the core ring area and the fiber cladding $\Delta n_2 \sim 0.03$, corresponding to the fiber numerical aperture NA 0,3; second, there was a specific ratio between the core ring area thickness 21 ± 1 micron and central dip diameter of 11 ± 1 micron that had to be maintained; and finally, there had to be a small refractive index difference between central dip area and the fiber cladding $\Delta n_1 \sim 0.003$-0.01. In addition, the fiber diameter had to be equal to 125 micron for convenient comparison of the designed fiber waveguide characteristics and regular single-mode fiber ones.

In our first efforts, we used standard MCVD (Modified Chemical Vapor Deposition) technique to prepare the fiber preforms. Germanium was used to dope fused silica layers deposited on the inner substrate silica tube surface. A calculated germanium concentration corresponded to the desired Δn_2 value of 0.03 was used. The dip area was not specifically deposited because of the well-known phenomenon of germanium diffusion out of the preform center during a preform collapse, i.e., germanium "burn-off". Therefore, it was decided that the dip in the center of the preform refractive index profile should be prepared during the final stage of fiber preform fabrication. We have prepared two preforms using this technique. In each

case, fifty layers with the same germanium concentration were deposited. This was the number of layers we estimated as necessary to obtain a fiber with standard diameter of 125 micron and satisfy the geometric constraints described above. In both cases, the stress due to the high concentration of the germanium caused the preform to crack. The first preform cracked during the deposition process, and the second one during the preform collapse. This showed that the germanium concentration was too high to prepare doped fused silica with the desired calculated value of Δn_2. The crack probability is high and this fabrication technique was not promising, particularly considering the time required to deposit the large number of layers.

A second fiber preform fabrication process based on the modified MCVD method using aerosol delivery technique was used to prepare the preform. It was chosen because the aerosol delivery technique permits to deposit silica glass layers doped with any rare earth elements as well as ions that have a larger atomic number and thus, a larger refractive index. With a larger refractive index, a lower dopant concentration reduces internal stresses inside the fiber preform, and thus reduces the probability for the crack. It not possible to find chemical precursors for ions with a large atomic number using standard MCVD technique, and aerosol delivery is the only technique that can be used for the convective transport of such ions. Metal-organic precursors containing tantalum (Ta) ions were used to obtain large Δn_1 values with this technique.

Three additional fiber preforms were fabricated using the aerosol delivery technique. The first preform had 24 deposited layers to form a core ring area with Δn_2 value and one layer to form a dip area with Δn_1 value. A precursor with a tenfold reduction in the amount of Ta was used for the inner layer. Since this was an initial attempt to be used for guidance in subsequent preforms, little attention was paid to the fiber diameter. Consequently, number of layers was smaller than for the Ge-doped preforms.

The refractive index profile of the first Ta-doped preform is shown in Figure 6. The absolute value of Δn_2 is large (Δn_2~0.05). Unfortunately, the required dip area was practically eliminated as a consequence of the diffusion of Ta ions into the center of the preform.

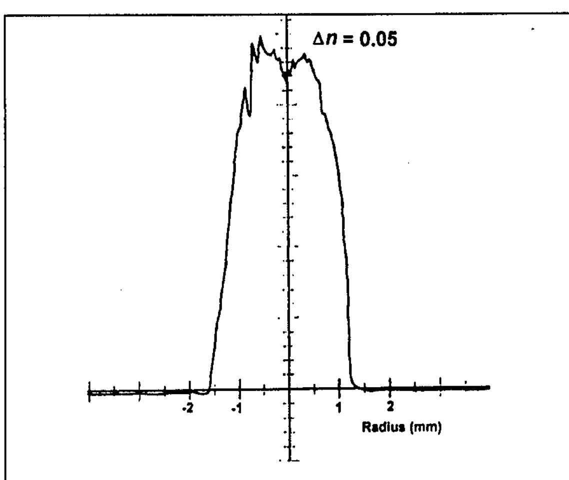

Figure 6: Index profile of the first preform

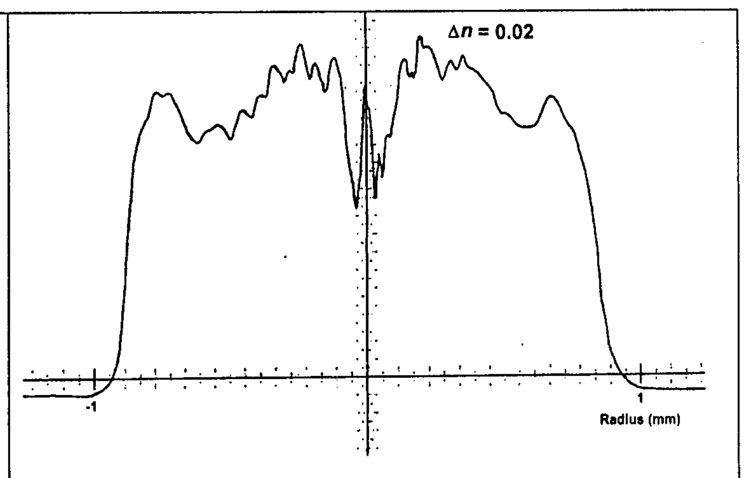

Figure 7: Index profile of the second preform

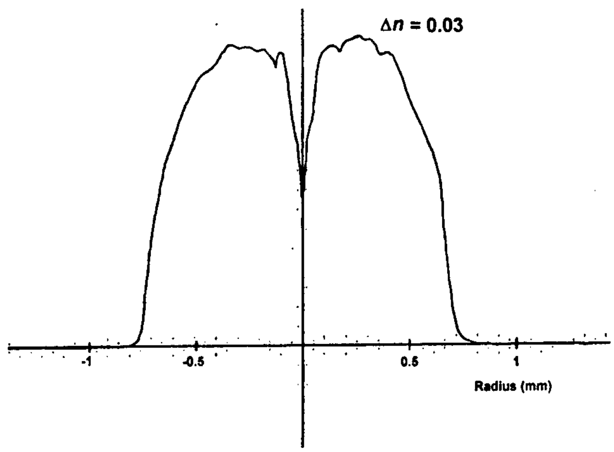

Figure 8: Refractive index profile of the final preform

A second preform was fabricated and the number of layers for the region of decreased refractive index was increased by a factor of 2. In addition, the preform collapse temperature was decreased to reduce diffusion. The refractive index profile is shown in Figure 7. The diameter of the dip region is too small, and again for this case the influence of tantalum diffusion dominates.

The third preform was fabricated to evaluate the process of tantalum diffusion. Five layers with Ta were deposited to form a core ring area and additional five layers of pure fused silica (without Ta) were deposited to form a central dip. Refractive index profile is shown in Figure 4. The absolute value of Δn_2 approximates the target value, but the area of the central dip is much smaller than expected. In addition, the value of Δn_1 is much larger than calculated as a consequence of dopant diffusion.

The second stage of the project was directed to a different fiber preform fabrication method to overcome the problem of core diffusion during the high collapse temperature of the preform. We employed a rod-in-tube technique to form the central dip area and a down doped silica tube was used to form the core ring area.

In Fig. 9a we show the fiber refractive index profile with a fused silica (SiO_2) substrate tube for the cladding. To use rod-in-tube method the central dip area has to be fabricated with doped material with refractive index larger than fused silica. If, however, we wish to use a pure fused silica rod for the central part of the preform, the refractive index value for the inner part of the substrate tube has to be less than that of silica (Figure 9b). The width of this area of reduced refractive index has to be sufficient to not change the waveguide properties of the designed fiber. The depth of this area should be not smaller than 0.003.

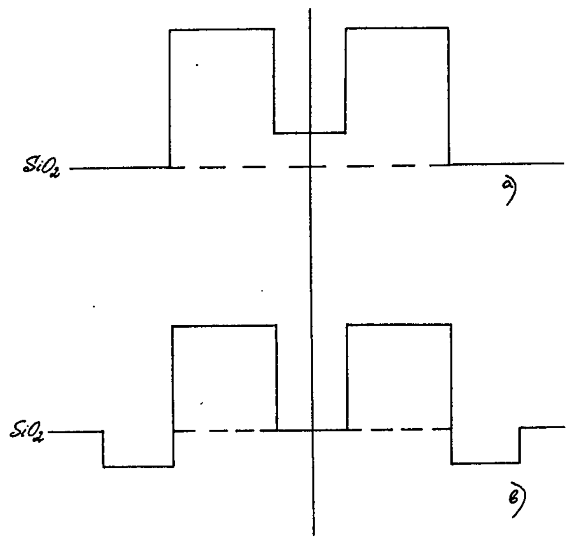

Figure 9: Compound refractive index profile with silica cladding (a) and with pure silica central dip (b).

A silica substrate tube whose inner wall has been down-doped with fluorine was used to fabricate a Ta-doped preform with hole in the center. That is, first several layers of fluorine doped soot were deposited on the inside of the silica substrate tube, and this was followed by many layers of up-doping with Ta precursors. To obtain the necessary decrease in the index of refraction in the center, a 1-mm thick fused silica rod was inserted in the substrate tube to form the dip area. The tube and rod were subsequently collapsed to form a solid preform rod. Measured refractive index profile is shown in Fig. 10. Geometrical parameters of the preform were arbitrary. This result confirms the possibility to use SF_6 etching process to obtain a fluorine-doped region with the desired refractive index value. However, the diffusion of Ta ions during the preform collapse changed the central part refractive index value.

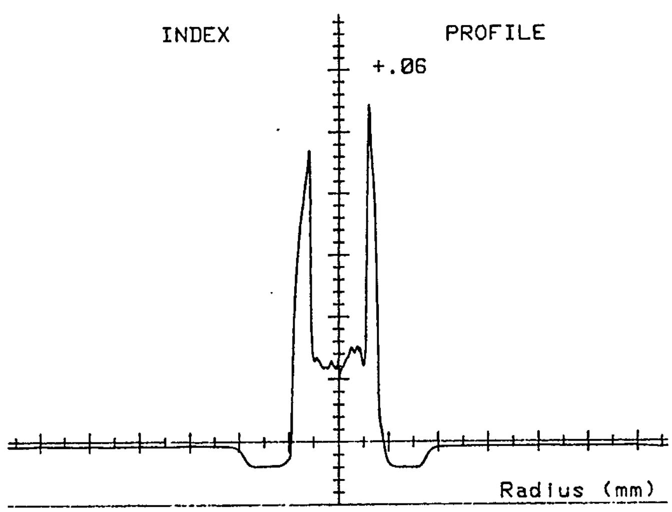

Figure 10: Refractive index profile of preform after its collapsing

Our next attempt used a 1-mm fused silica rod in conjunction with a Ge-doped preform with the hole in the center to pull the fiber without the preform collapse, i.e., the traditional rod-in-tube method. A cross section of the drawn fiber is shown in Figure 11. It is clear that no diffusion occurred during this fabrication process. The dark spot in the fiber center is the dip area with unchanged fused silica refractive index.

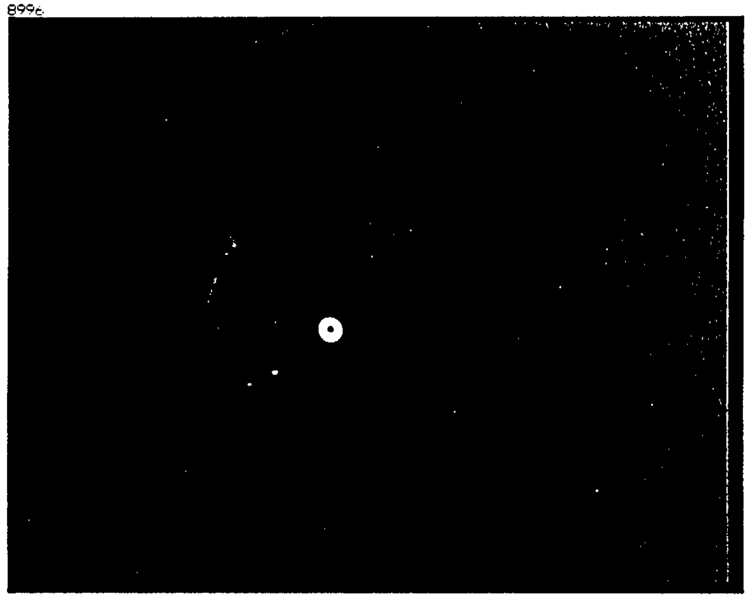

Figure 11: Picture of the fiber cross section under microscope.

In the third stage of this project we focused on a rod-in-tube optical fiber fabrication method to overcome the deficiencies of our previous attempts to prepare the fiber of Figure 1.

Due to a constraint of time, only two more fiber preforms were fabricated and pulled into fibers. As above, we down-doped the inner wall of a silica substrate tube with fluorine, and then up-doped with Ta, leaving a hole in the center into which a silica rod was to be inserted. One of the preforms refractive index profile is shown in Figure 12. The central dip that gives the value of the refractive index was not calibrated due to the air gap in the center. To check the method of measurement a portion of the preform was completely collapsed to form a solid glass rod. The refractive index profile was measured second time (see Figure 13). This indicates that the use of fluorine and tantalum is optimal to form two ring areas with modified refractive index: -0.003 for the outer ring and >0.03 for the inner ring (when compared with pure fused silica). If a fused silica rod would be substituted for the air gap in the preform center (Figure 12) the optical fiber design will be close to calculated one.

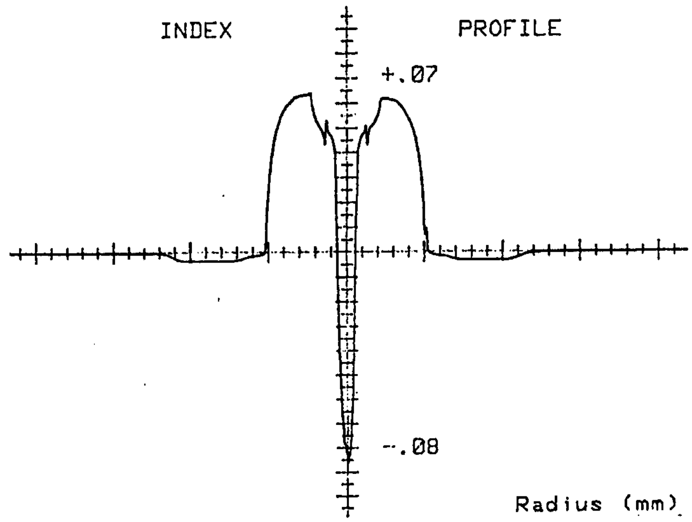

Figure 12: **Refractive index profile of the preform**

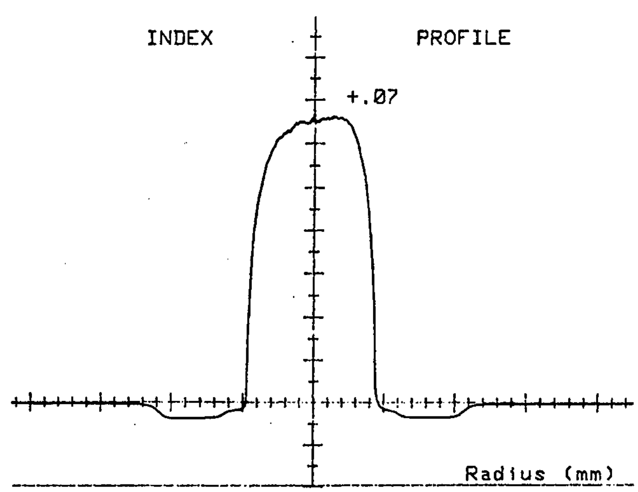

Figure 13: **Refractive index profile of the preform after collapsing**

The required diameter of the fused silica rod depends on the thickness of the tantalum doped layers. For our preforms, it was 425 micron. We made three attempts to pull optical fibers from two preforms described above. Because of the arbitrary diameter of the uncollapsed inner cylinder, the pulling temperature was different in each case. Three optical fiber cross sections are shown in Figures 14-16. In our first attempt, the delicate silica rod broke, and two cores fiber was obtained (Figure 14). The temperature in the second attempt was too low to collapse the air gap and the fiber has a hole in the center with the silica rod attached to the inner wall (Figure 15). The temperature was increased in the third attempt and solid optical fiber has been drawn but with asymmetrical silica rod position (Figure 16). We believe that these deficiencies can be eliminated with a few further attempts to obtain this fiber design.

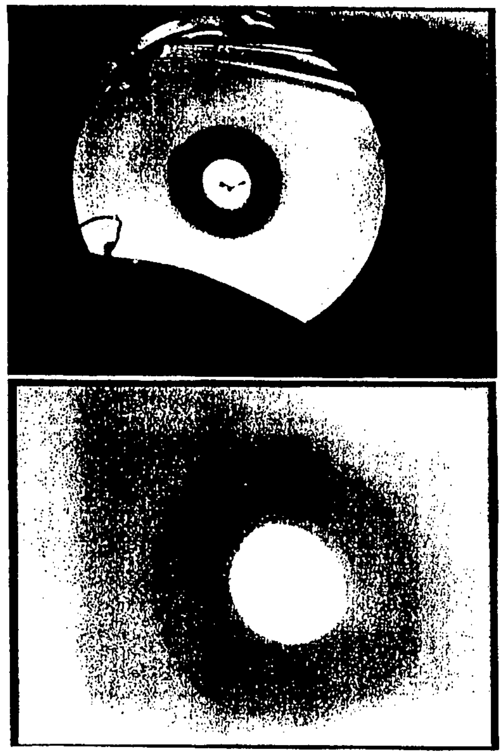

Figure 14: **Two-core fiber obtained from broken preform**

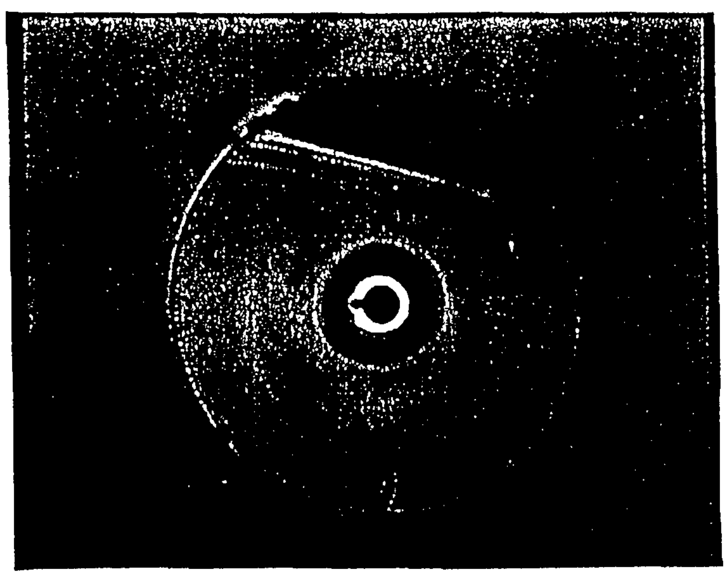

Figure 15: **Fiber with a hole in the center with silica rod on the inner wall**

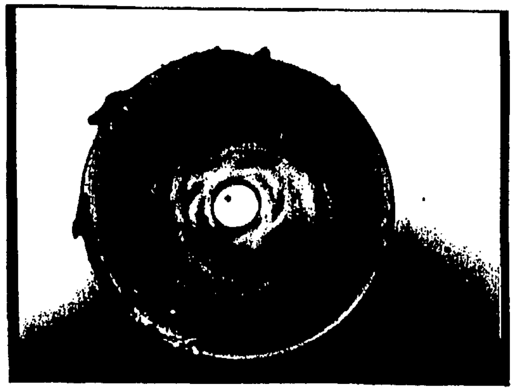

Figure 16: Fiber with asymmetric position of silica center

Increasing the number of deposited layers with tantalum and, as consequence, increasing the diameter of silica rod in rod-in-tube method will improve the fiber quality and eliminate the problems described above.

On the fourth stage of the project the number of Ta-doped deposited layers was increased up to 40. The calculated silica rod diameter was to be ~700 micron. Because the deposition of each layer is a lengthy process requiring adequate drying and sintering to prevent the formation of bubbles (~2 hours), it took 5 days (with some breaks) to finish this last preform. Large refractive index difference between the substrate tube material and the deposited layers, along with large temperature gradients were the reasons why this last perform was asymmetric with some bubbles inside. This preform cracked at the final step of the fabrication process.

4. Conclusion

In conclusion, properties of the compound-core fiber are theoretically investigated in detail. Stable sharp-peak mode operation of the fiber is demonstrated. The technological methods are developed to fabricate silica fibers with large value of Δn_2 during the first two stages of the experimental part of the project. MCVD method with aerosol delivery technique permits to fabricate optical fibers with Δn_2 =0.05-0.07. We believe this is the highest value of raised refractive index that has been obtained in a silica fiber. The central dip problem was not solved at the time because of an uncontrollable dopant ion diffusion. The last two stages of the project were directed to the new fiber preform fabrication method to overcome this problem. A rod-in-tube method was used to form the central dip area and Ta-doped silica tube was used to form the core ring area. Fiber with designed refractive index profile but with no concentric fiber core position was drawn. A total of seven fiber performs were fabricated. We believe that the results we obtained indicate a real possibility to produce an optical fiber with the desired design refractive index profile.

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